THE ASTROPHYSICAL JOURNAL, 234:L51–54, 1979 November 15

DISCOVERY OF AN X-RAY STAR ASSOCIATION IN VI CYGNI (CYG OB2)

F. R. HARNDEN, JR., G. BRANDUARDI, M. ELVIS,[1] P. GORENSTEIN, J. GRINDLAY, J. P. PYE,[1] R. ROSNER, K. TOPKA, AND G. S. VAIANA[2]
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts
Received 1979 June 26; accepted 1979 July 26

ABSTRACT

A group of six X-ray sources located within 0°4 of Cygnus X-3 has been discovered with the *Einstein* Observatory. These sources have been positively identified and five of them correspond to stars in the heavily obscured OB association VI Cygni. The optical counterparts include four of the most luminous O stars within the field of view and a B5 supergiant. These sources are found to have typical X-ray luminosities L_x (0.2–4.0 keV) $\sim 5 \times 10^{33}$ ergs s^{-1}, with temperatures $T \sim 10^{6.8}$ K and hydrogen column densities $N_{\rm H} \sim 10^{22}$ cm^{-2}, and therefore comprise a new class of low-luminosity galactic X-ray sources associated with early-type stars.
Subject headings: stars: early-type — X-rays: sources

I. INTRODUCTION

The OB association VI Cygni (Cygnus OB2), located within 0°4 of the powerful galactic X-ray source Cygnus X-3, has long attracted the attention of optical astronomers (Johnson and Morgan 1954; Schulte 1958). Walborn (1973) has found many members of the association, which is characterized by unusually heavy interstellar reddening, to be superluminous within their spectral type. The association is distinguished by VI Cygni No. 12, a B5 supergiant which is one of the visually most luminous stars in the galaxy ($M_v = -10$: Sharpless 1957; Souza 1979), and by VI Cygni No. 5, a contact binary whose primary is one of the most massive stars in the galaxy ($\sim$60 $M_\odot$: Leung and Schneider 1978). Luminous, early stars are known to be sources of strong stellar winds (see Morton 1967; Snow and Morton 1976; and review by Conti 1978*a*), and have been extensively studied in the radio, infrared, visible, and UV (see Cassinelli 1979, and references therein).

In this *Letter* we report the detection with the *Einstein* Observatory (*HEAO 2*) of six discrete sources of soft X-ray emission within the VI Cygni association, as well as the identification of the optical counterparts of five of these sources with O and B stars in the association.

II. EXPERIMENT AND ANALYSIS

The discovery of soft X-ray emission from the VI Cygni region occurred serendipitously during the course of extended observations of the galactic X-ray source Cygnus X-3, carried out 1978 December 15–17 with the imaging proportional counter (IPC) at the focus of the arcsec resolution imaging X-ray optics of the *Einstein* Observatory (Giacconi *et al.* 1979). This combination provides an area of $\sim$100 cm^2 at 1.5 keV and yields a two-dimensional image with $\sim$arcmin resolution over a field of view of 1° × 1°. The IPC energy range of 0.2–4 keV is determined at low energy by absorption in the entrance window and at high energy by loss of mirror reflectivity. Pulse-height analysis of the proportional counter signals gives a FWHM energy resolution of $\sim$100% at 1.5 keV.

Follow-up observations, begun 1979 May 17.8 with the high-resolution imager (HRI; resolution $\sim$4″), provided $\sim 10^4$ s of supplementary data on the newly discovered sources.

a) *Existence and Extent*

Figure 1*a* (Plate L15) presents the X-ray image of the Cyg X-3 region that we have obtained with a $\sim 10^4$ s exposure of the IPC. In addition to Cyg X-3, the image clearly shows the existence (at greater than 5 σ confidence) of at least five distinct sources; the X-ray positions of these sources, labeled A through E, are listed in Table 1.

The IPC data for all sources except B are consistent with point sources; and source B is resolved by the HRI into two discrete sources designated B and B′ and separated by 1′9, thereby raising the total number of sources to six. The HRI data for source A suggest at least two emitters within a 0′3 region; pending further analysis of the HRI data, however, we set a conservative size upper limit of 20″ on the diameters of the six individual sources.

In addition to the six sources mentioned above, there are at least two regions (located $\sim$10′ east of Cyg X-3 and $\sim$7′ west of source E) with localized counting rates significantly in excess of the average background. The similarity of the pulse-height spectra from these regions to those of the identified sources provides evidence for additional, weaker sources present in the field.

b) *Source Location and Identification*

The IPC source locations given in Table 1 (which also includes a summary of optical properties) are indicated

[1] Also Physics Department, University of Leicester, Leicester, England.
[2] Also Osservatorio Astronomico di Palermo, Palermo, Italy.

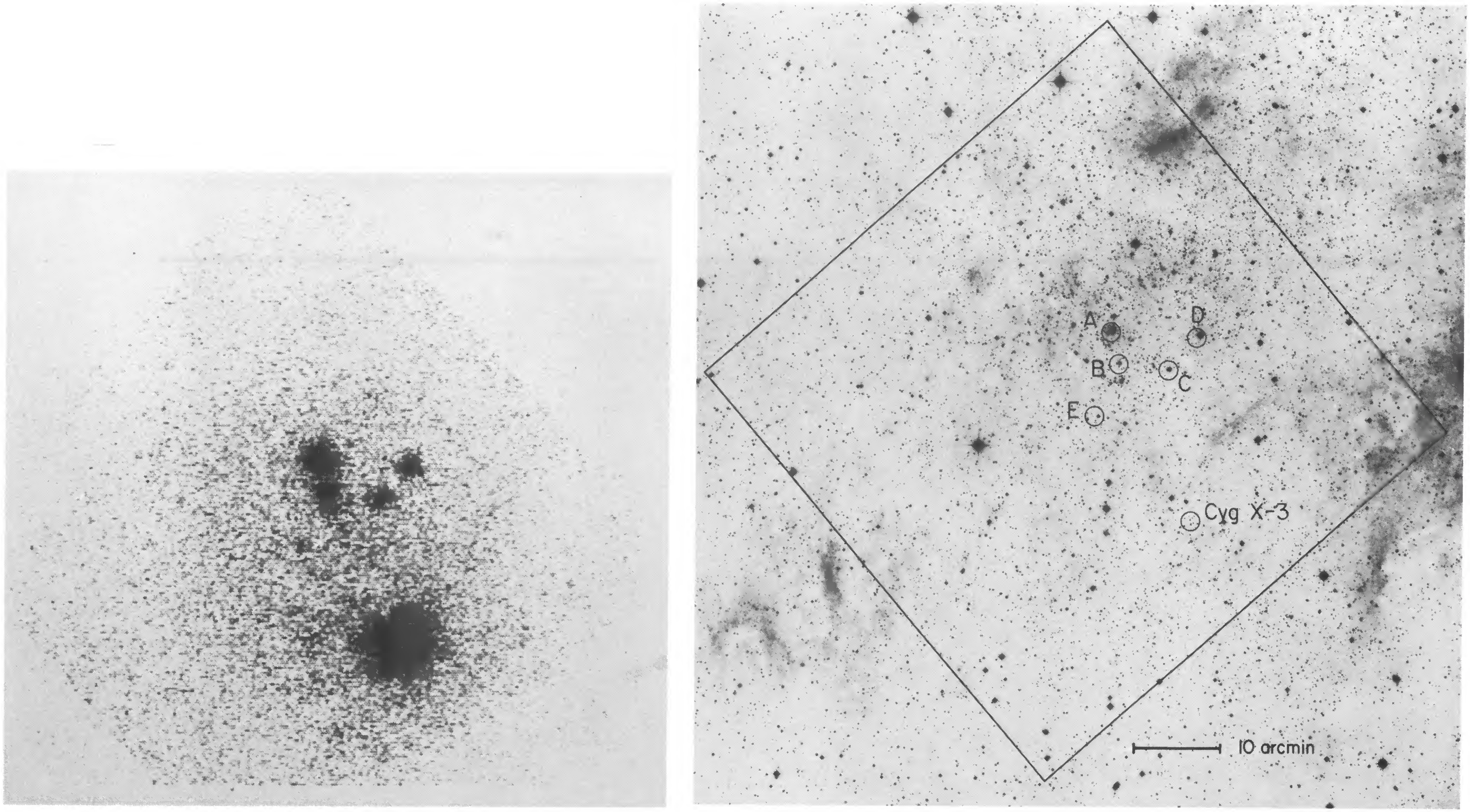

FIG. 1.—Region observed during the first exposure to the X-ray sky with the imaging proportional counter (IPC) of the *Einstein* Observatory. North is up and east is to the left in each portion of the plate. (*a*) Arcmin-resolution X-ray image; the gray scale is approximately logarithmic, with denser and darker regions corresponding to higher 0.2–4 keV X-ray intensity. The bright source at lower right is Cygnus X-3. The composite image, containing $\sim 10^4$ s of data, is a superposition of 11 separate exposures of a region which fortuitously includes the OB star association. (*b*) Reproduction of the Palomar Sky Survey red print, with the X-ray locations (labeled A through E and Cyg X-3) superposed as $\sim 1'$ radius circles; the scale is indicated at the lower right. The large trapezium of stars (A-D) consists of the four most luminous stars of the VI Cygni OB association.

HARNDEN *et al.* (*see* pages L51 and L52)

in Figure 1*b* (Plate L15) on the Palomar Sky Survey red print with 90% confidence error circles of $\sim 1'$ radius; four of the sources match the positions of the four brightest stars in the association. For the fifth source (*E*), the X-ray position coincides with a faint star ($m_v > 13$) of undetermined spectral type; efforts to study this optical counterpart are currently underway. The HRI locations for the five IPC sources agree with the optical positions to within $\sim 4''$, confirming these identifications, while the location of the sixth source (B′) coincides with our measured optical position ($\alpha = 20^h31^m20^s.9$, $\delta = 41°03'01''$) for Schulte (1958) star No. 22, thereby also confirming this star as an X-ray emitter of intensity comparable to that of source E.

c) Intensities, Spectra, Luminosities

The spectral analysis procedure used here begins with the determination of count rates above background in IPC pulse-height intervals corresponding to the 0.2–0.5 keV, 1.5–4.0 keV, and 0.2–4.0 keV bandpasses. The mean source temperature and hydrogen column density are then determined by comparing the ratios of the bandpass count rates with the ratios derived from theoretical emission spectra of a solar-abundance thermal plasma subject to interstellar absorption, folded through the mirror and detector response.

The results of this analysis for the five IPC sources are presented in Table 2. Sources B, C, and D form a fairly homogeneous class with regard to temperature and soft X-ray luminosity; the X-ray and optical luminosities are well correlated. In the case of the brightest X-ray source (source A) it must be noted that the optical counterpart actually consists of four components, only the visually most luminous of which is listed in Table 1. The HRI data from this source suggest emission from at least two of the components, the strongest of which is the brightest optically.

Since the X-ray sources correspond to the intrinsically brightest (visually) association members in the field, it is sensible to test the hypothesis that all members emit X-rays and that the remaining association members in the field of view are simply insufficiently luminous to have been detected in our observations. Adopting an X-ray to visual luminosity ratio $L_x/L_{\rm visual} \sim 2 \times 10^{-4}$ leads to the conclusion that the next most luminous star with comparable exposure should have IPC and HRI counting rates below the detection thresholds for these observations. Taking the observed scatter in $L_x/L_{\rm visual}$ into account, we conclude that the observations are consistent with the above hypothesis and that the two regions of excess emission imply the existence of additional, highly reddened association members.

The study of the temporal variation in X-ray inten-

TABLE 1

X-Ray Source Positions and Optical Identifications

X-Ray Source	IPC Position (1950) α(hms)			δ(° ′ ″)			Cyg OB2 Star No.	Optical Position[b] (1950) α(hms)			δ(° ′ ″)			Spectral Class	m_v	M_v	$(m-M)_0$
A..........	20	31	27	41	08	31	8A[a]	20	31	27.1	41	08	32	O6 Ib	9.0	−7.2	10.4
B..........	20	31	23	41	04	50	9	20	31	22.7	41	04	51	O5 If	10.8	−7.3	11.0
C..........	20	30	53	41	04	11	12	20	30	53.2	41	04	12	B5 Ia	11.5	−10	...
D..........	20	30	36	41	07	49	5	20	30	34.7	41	08	03	O7 Ia[c]	9.1	−7.8	10.8
E..........	20	31	37	40	58	59	...	20	31	35.5	40	58	54	...	...	...	...

Note.—The optical data are primarily from the recent compilation of Humphreys 1978, and incorporate the work of Walborn 1973, who has revised and extended to two-dimensional spectral classifications, the early spectroscopic work of Johnson and Morgan 1954 and Schulte 1958. As a result of Walborn's analysis, several previous large uncertainties regarding the intrinsic optical luminosity of the O stars in the association have been substantially reduced; and a luminosity classification scheme for early O stars has been established (see also Humphreys 1978).

[a] Source A coincides with a quartet of O stars; star 8A listed here is the brightest star in the quartet.

[b] Optical positions were determined from the Sky Survey print (RMS accuracy $\sim 1''.4$).

[c] Contact binary; secondary is O6 (Bohannan and Conti 1976).

TABLE 2

Summary of IPC Observations of VI Cygni (Cyg OB2) Region

X-Ray Source	Intensity (cts s^{-1})	log T (K)	log $N_{\rm H}$ (cm^{-2})	F_x[a](0.2–4.0 keV) (ergs s^{-1} cm^{-2}) ($\times 10^{-12}$)	L_x[b](0.2–4.0 keV) (ergs s^{-1}) ($\times 10^{33}$)	L_x(0.2–4.0 keV)/ $L_{\rm visual}$ ($\times 10^{-4}$)
A........	0.15±0.01	6.9±0.1	22.2±0.1	3.1 ±0.2	19.3±1.3	6.3±0.5
B........	0.075±0.009	7.0±0.1	22.0±0.1	1.5 ±0.1	3.5±0.4	1.0±0.1
C........	0.045±0.009	6.8±0.3	22.2±0.2	0.89±0.04	9.0±0.8	2.2±0.2
D........	0.056±0.009	6.7±0.2	22.0±0.1	1.1 ±0.1	7.0±0.7	1.4±0.2
E........	0.014±0.007	6.7±0.3	22.0±0.2	0.27±0.04	1.7±0.2	...

[a] Detected flux at top of the atmosphere.

[b] Mean distance (1.8 kpc) of the association has been used for calculation of intrinsic X-ray luminosities.

sity of these sources will undoubtedly be helpful in understanding the underlying emission mechanisms; but our sensitivity to temporal variations is limited; and we have not been able to find evidence for variability.

III. DISCUSSION

Although the optical appearance of the VI Cygni sources superficially resembles that of some strong galactic X-ray sources, such as Cyg X-1, known to be close binaries in which a compact secondary orbits a luminous supergiant primary, the two types of sources are sharply distinguished by their X-ray properties. The association sources have substantially lower temperatures ($kT \lesssim 1$ keV versus $kT > 8$ keV) and much lower luminosities ($\sim 10^{34}$ ergs s^{-1} versus $\sim 10^{37}$ ergs s^{-1}). We therefore conclude that the VI Cygni sources constitute a new class of low-luminosity galactic X-ray sources quite distinct from the high-luminosity compact X-ray sources. This conclusion is strengthened by the discovery of X-ray emission from early-type stars of luminosity class V and III in the η Carinae complex (Seward *et al.* 1979).

A detailed comparison between models and observational results is beyond the scope of this *Letter*, but we list below several alternative models which might account for the X-ray emission.

a) Single-Star Models

Cold stellar wind.—The optical counterparts of the X-ray sources reported here occupy a region in the H-R diagram known to be associated with large mass-loss rates ($\dot{M} > 10^{-8}\ M_\odot$ yr^{-1}; viz., Conti 1978*a*), and therefore we expect them to have strong winds. One class of models seeking to explain these strong winds holds that the extended stellar atmosphere (including the wind) is relatively cool ($T \lesssim 10^5$ K; see Cassinelli, Castor, and Lamers 1978 for a critique of these models); these models are at best incomplete because our observations imply the presence of a very hot ($T \gtrsim 10^{6.7}$ K) plasma near the star.

Shocked stellar wind.—Elaborations of cool-wind models for early-type stars involve the interaction of winds with the ambient interstellar matter, leading to shocked winds and soft X-ray emission (viz., Castor, McCray, and Weaver 1975) which might account for our observations. However, our determinations of source temperature and spatial extent are in conflict with expectations based upon these shocked wind models (cf. Castor, McCray, and Weaver 1975; Weaver *et al.* 1977); the sources we observe are somewhat hotter and much smaller in volume than the sources predicted by the models. Hence, the sources we observe cannot be due to such "bubbles."

Warm stellar wind with photoionizing corona.—In another class of models, coronae associated with strong winds produce X-ray emission, either via mechanical heating at the stellar surface (Hearn 1975; Cassinelli, Olson, and Stalio 1978) or via instabilities in the wind itself (Thomas 1973; Cannon and Thomas 1977). For example, Cassinelli and Olson (1979) calculated the expected X-ray flux from a hypothesized coronal region of early-type supergiants (e.g., ζ Pup) by assuming a coronal temperature of 5×10^6 K, and by demanding a sufficiently large volume emission measure to enable the softer component of the X-ray emission to photoionize the oxygen in the cool ($T < 10^5$ K) wind. The X-ray luminosities in the 0.2–4.0 keV bandpass derived for the VI Cygni sources (Table 2) are in approximate agreement with predictions of such a model, but the intrinsic column densities required by the model ($N_{\rm H} \sim 10^{23}$ cm^{-2}) are much larger than those we have inferred from our observations. The absorption deduced from the X-ray data is consistent with that implied by the interstellar reddening.

b) Binary Models

Systems containing a collapsed secondary.—Some theoretical models predict emission from accreting winds in close binary systems (Davison and Ostriker 1973; Lamers, van den Heuvel, and Pettersen 1976), particularly during the "quiet" phase (van den Heuvel 1976) preceding strong mass exchange associated with high-luminosity compact binary X-ray sources. For example, Lamers *et al.* and Conti (1978*b*) describe a scenario in which a collapsed companion accretes matter from an evolving O star, leading to a long-lived (and hence common), low-luminosity source; this state is a precursor of the eventual high-luminosity stage which results when the O star evolves to the supergiant stage. Regardless of the luminosity state, the source is expected to have a rather high temperature because accretion occurs onto a degenerate object. In contrast, the optical counterparts of the VI Cygni sources have already evolved into luminous O supergiants, and yet still have relatively low temperature and luminosity. The relative homogeneity in the observed X-ray properties of the VI Cygni and η Carinae X-ray stars, and the fact that in VI Cygni we observe all association members within our detection limits, are inconsistent with the above scenario. It therefore seems unlikely that models of close compact binaries can explain the sources we observe.

On the other hand, a model with a compact object in a well-separated binary could account for the X-ray luminosities we observe (such a suggestion has been made [cf. Becker *et al.* 1979 and references cited therein] for X Persei, a $\sim 10^{34}$ ergs s^{-1} X-ray source), but would have difficulty with the low temperatures derived for the association sources.

Systems without a compact object.—The observed X-ray emission could arise as a result of accretion in a binary system whose components are both nondegenerate stars. Naive application of a simple accretion model (viz., Lamers, van den Heuvel, and Pettersen 1976) yields rough agreement with the observed luminosities but somewhat lower temperatures ($T \sim 10^6$ K). However, we note that close, massive, nondegenerate binaries are likely to lose mass from the system as a whole, rather than transfer mass from one component to the other (Flannery and Ulrich 1977). Particularly interesting from this point of view is the optical counterpart of source D, VI Cygni No. 5, which is a contact binary of luminous supergiants (Bohannan and Conti 1976; Leung and Schneider 1978) and shows substantial evidence for a large mass loss from the system as a whole ($\dot{M} \sim 10^{-5} M_{\odot}\, yr^{-1}$; Bohannan and Conti 1976). At least for star No. 5, therefore, accretion onto a nondegenerate star does not provide a reasonable explanation for the observed X-ray emission.

An alternative model for the X-ray emission from nondegenerate binary systems involves shocks created by the collision of stellar winds. For VI Cygni star No. 5, for example, the model of Cooke, Fabian, and Pringle (1978) predicts an X-ray luminosity and a temperature in rough agreement with our results for source D. There is some doubt whether such models are at all applicable to contact binaries (like VI Cygni No. 5); and furthermore, we note that the optical counterparts of the remaining X-ray sources are not at present known to be binaries, so that these model calculations may not be applicable.

IV. SUMMARY AND CONCLUSIONS

We have detected an association of at least six new X-ray sources and have identified five of them with early-type stars in the VI Cygni OB association. The observed X-ray properties set these sources apart from previously known sources, thereby demonstrating the existence of a new class of low-luminosity galactic X-ray sources. Our observations definitely cannot be explained by cold wind, shocked ("bubble") wind, or close-binary accretion models; and models involving well-separated compact binaries, or colliding winds (in a close binary system) have difficulty producing all of the observed characteristics. Models of photoionizing coronae yield rough agreement with the X-ray luminosities and temperatures, but require larger column densities than we have found for the X-ray star association.

We gratefully acknowledge the help of the many scientists, engineers, program managers, students, computer programmers, technicians, and secretaries without whom the *HEAO 2* (*Einstein*) program would not have been possible. We thank J. Ostriker for useful discussions and B. Duncan for her constant efforts in preparing this manuscript for publication. This research was sponsored under NASA contract NAS8-30751. Two of us (M. E. and J. P.) received financial support from the British Science Research Council; two of us (G. V. and R. R.) acknowledge partial support from the Langley Abbot Program of the Smithsonian Institution; and one of us (G. V.) also acknowledges partial support from the CNR and CRRN (Italy).

REFERENCES

Becker, R. H., Boldt, E. A., Holt, S. S., Pravdo, S. H., Robinson-Saba, J., Serlemitsos, P. J., and Swank, J. H. 1979, *Ap. J.* (*Letters*), **227**, L21.
Bohannan, B., and Conti, P. S. 1976, *Ap. J.*, **204**, 797.
Cannon, C. J., and Thomas, R. N. 1977, *Ap. J.*, **211**, 910.
Cassinelli, J. P. 1979, *Ann. Rev. Astr. Ap.*, **17**, in press.
Cassinelli, J. P., Castor, J. I., and Lamers, H. J. G. L. M. 1978, *Pub. A.S.P.*, **90**, 496.
Cassinelli, J. P., and Olson, G. L. 1979, *Ap. J.*, **229**, 304.
Cassinelli, J. P., Olson, G., and Stalio, R. 1978, *Ap. J.*, **220**, 573.
Castor, J. I., McCray, R., and Weaver, R. 1975, *Ap. J.* (*Letters*), **200**, L107.
Conti, P. S. 1978*a*, *Ann. Rev. Astr. Ap.*, **16**, 371.
———. 1978*b*, *Astr. Ap.*, **63**, 225.
Cooke, B. A., Fabian, A. C., and Pringle, J. E. 1978, *Nature*, **273**, 645.
Davidson, K., and Ostriker, J. P. 1973, *Ap. J.*, **179**, 585.
Flannery, B. P., and Ulrich, R. K. 1977, *Ap. J.*, **212**, 533.
Giacconi, R., *et al.* 1979, *Ap. J.* **230**, 540.
Hearn, A. G. 1975, *Astr. Ap.*, **40**, 277.
Humphreys, R. M. 1978, *Ap. J. Suppl.*, **38**, 309.
Johnson, H. L., and Morgan, W. W. 1954, *Ap. J.*, **119**, 344.
Lamers, H. J. G. L. M., van den Heuvel, E. P. J., and Pettersen, J. A. 1976, *Astr. Ap.*, **49**, 327.
Leung, K. C., and Schneider, D. P. 1978, *Ap. J.*, **224**, 565.
Morton, D. C. 1967, *Ap. J.*, **147**, 1017.
Schulte, D. H. 1958, *Ap. J.*, **128**, 41.
Seward, F. D., Forman, W. R., Giacconi, R., Griffiths, R. E., Harnden, F. R., Jr., Jones, C., and Pye, J. P. 1979, *Ap. J.* (*Letters*), **234**, 55.
Sharpless, S. 1957, *Pub. A.S.P.*, **69**, 239.
Snow, T. P., and Morton, D. C. 1976, *Ap. J. Suppl.*, **32**, 429.
Souza, S. P. 1979, private communication.
Thomas, R. N. 1973, *Astr. Ap.*, **29**, 297.
van den Heuvel, E. P. J. 1976, in *Structure and Evolution of Close Binary Systems*, ed. P. Eggleton (Dordrecht: Reidel).
Walborn, N. R. 1973, *Ap. J.* (*Letters*), **180**, L35.
Weaver, R., McCray, R., Castor, J., Shapiro, P., and Moore, R. 1977, *Ap. J.*, **218**, 377.

G. Branduardi, M. Elvis, P. Gorenstein, J. Grindlay, F. R. Harnden, Jr., J. P. Pye, R. Rosner, K. Topka, and G. S. Vaiana: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138